DEVELOPMENT OF A LOW-COST WIRELESS ACCELEROMETER SENSOR PLATFORM (WASP) FOR MACHINE MONITORING APPLICATIONS

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DEVELOPMENT OF A LOW-COST WIRELESS ACCELEROMETER SENSOR PLATFORM (WASP) FOR MACHINE MONITORING APPLICATIONS

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To the students of Team Kurfess and the EPICS Program.

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Thank you to my loving mom, dad, and grandmother for their endless support and encouragement. They have taught me almost everything I know. But not eveything they know!

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LIST OF SYMBOLS AND ABBREVIATIONS

CNC	Computer Numeric Controlled
IoT4MFG	Internet of Things for Manufacturing
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
WASP	Wireless Accelerometer Sensor Platform
XML	Extensible Markup Language

SUMMARY

The modern Industrial revolution, or Industry 4.0, has dramatically expanded the capabilities of digital manufacturing. However, modern machines with monitoring capabilities are extremely expensive to purchase and take years of operation to recoup the capital cost. A need exists to provide a low-cost Internet-of-Things for Manufacturing (IoT4MFG) sensor platform that can provide accurate monitoring and analysis capabilities on a machine of any age. The Wireless Accelerometer Sensor Platform (WASP) is an extremely low-cost, wireless, and robust solution to upgrade the monitoring capabilities of manufacturing machines to a modern standard. This platform provides a flexible capability to modularly handle analog and digital sensors of standard communication protocols, as well as a standard set of base sensors including an accelerometer. Additionally, optimal placement of accelerometers on a machine is important for the proper measurement of vibrations. Commercial sensors are commonly fastened to the machine through permanent means without proper verification of positional vibration acquisition. A need exists to verify proper placement and function of these sensors. The WASP implements a live vibration monitor with a mobile phone app through Bluetooth Low Energy communication. Combined with a semi-permanent magnetic mount design, the sensors platform allows for precise placement and convenient adjustment to ensure optimal vibration measurement. The design methodology and verification process pursued to develop the WASP are presented. A case study was completed to demonstrate the technology on a manual lathe where machine vibration was measured. The WASP accelerometer was evaluated for accuracy with a spectrum of known input frequencies and results were compared against a high quality baseline accelerometer.

CHAPTER 1. INTRODUCTION

1.1 Overview of Current Manufacturing Equipment

Digital manufacturing is continuing to push the limits of existing manufacturing equipment. Most modern manufacturing equipment includes process monitoring capabilities including communication technologies such as MTConnect [1] and UPC-UA [2]. However, modern manufacturing equipment is very expensive to purchase. Many companies do not want to make the capital investment and purchase new machines when continual maintenance of their current machines is relatively cheap in comparison. Yet, older equipment often cannot reap the efficiency benefits provided by modern machine monitoring technologies. A need exists to provide a low-cost solution to retrofit these machines with modern machine monitoring capabilities.

Numerous external commercial sensors have been developed in the last five years to wirelessly monitor manufacturing operations and determine machine health. The Bosch XDK Cross Domain Development Kit [3] and the Fluke Vibration Sensor [4] are examples of commercial sensor packs that contain accelerometers to measure the vibration characteristics of manufacturing equipment. This data can be used at a base level to determine machine run time, overall usage analytics, and implement basic crash detection techniques. However, the cost of these sensors both exceed $200 per unit, also resulting in an expensive capital purchase to adequately monitor a handful of machines in a small machine shop.

Most commercial sensors fall into one of two categories; development kits designed for a user to create bench level prototypes from which a full product could later be outsourced and produced, or industry-ready products whose functions are very specific and highly limited from their full capabilities by the manufacturer. Both types of products prove difficult to implement as they either require significant custom development of process-specific applications, or a variety of specific sensors to capture the full range of data required.

Furthermore, access to raw data from the sensors is often limited as the development companies require use of their own propriety analytic software. This can severely limit higher-level analytics and adds another point of discontent for users.

A need exists to provide a low-cost machine monitoring solution that can be used both as a complete product and expandable platform. The desired product can be quickly implemented with base functionality and requires little or no development by the user. Additionally, its capabilities can be expanded if the user has a need for a custom implementation. This low-cost solution must strike a balance between an industry-ready machine monitoring product and a modularly expandable implementation platform.

CHAPTER 2. PREVIOUS WORK

2.1 MT Connect

Industry 4.0 has influenced a powerful array of technologies that allow manufacturing machines to be equipped with sensors, communication protocols, and remote access to enhance manufacturing processes. Among these are adoption of the MTConnect protocol [1], development of a common digital communication architecture [5], and accessibility to high performance computing platforms for commodity-based machine learning capabilities.

The MTConnect standard was originally developed in 2009 by a collaboration of researchers, industrial manufacturing partners, and digital networking specialists [6]. The Georgia Institute of Technology (Georgia Tech) became one of the first universities to participate and contribute to its development. MTConnect was designed to provide a common framework through which all manufacturing equipment, and especially Computer Numeric-Controlled (CNC) mills and lathes, could format and present data about their status. The MTConnect standard relies on Extensible Markup Language (XML) [7] formatting to organize data. It has been regularly updated since its first release to include additional capabilities. The most recent MTConnect release, version 1.4.0, included the structure to contain a list of tools and corresponding length offsets currently loaded into a CNC machine[2].

The MTConnect standard provides extremely powerful resources to the manufacturing industry. The standard has been adopted by the some of the world's largest machine tool companies such as MAZAK, OKUMA, DMG MORI, and can be installed on a plethora of machines. However, the MTConnect standard by itself only provides a common method of data formatting and methods through which the data can be accessed, leaving the details of data transmission, data storage, and analytics to the user.

While MTConnect is a standard, it is not a common implementation. Some aspects of the MTConnect platform are left to the machine tool company to modify. One machine tool company may choose to develop a slightly different implementation of MTConnect than a second machine tool company, although both conform to the official MTConnect standard. For example, one implementation of MTConnect may measure a machine's spindle velocity and assign it to a data tag labeled "L1Spindle", whereas another machine of similar capabilities but manufactured by a different company may label the same measurement "SpindleRev". Although both implementations conform to the MTConnect standard, slight differences may prove problematic as a machine shop begins to aggregate data from machines of various manufacturing companies.

2.2 Georgia Tech Digital Architecture

The Precision Machining Research Consortium at Georgia Tech has developed a robust data transmission and storage architecture for manufacturing equipment. The digital architecture is based on conversion of XML to Message Queuing Telemetry Transport (MQTT) messages [8], a common and industry accepted format that stores data in JSON packets [9]. Displayed in Figure 1, this digital architecture was designed to work with any machine, sensor, or platform that is MTConnect capable.

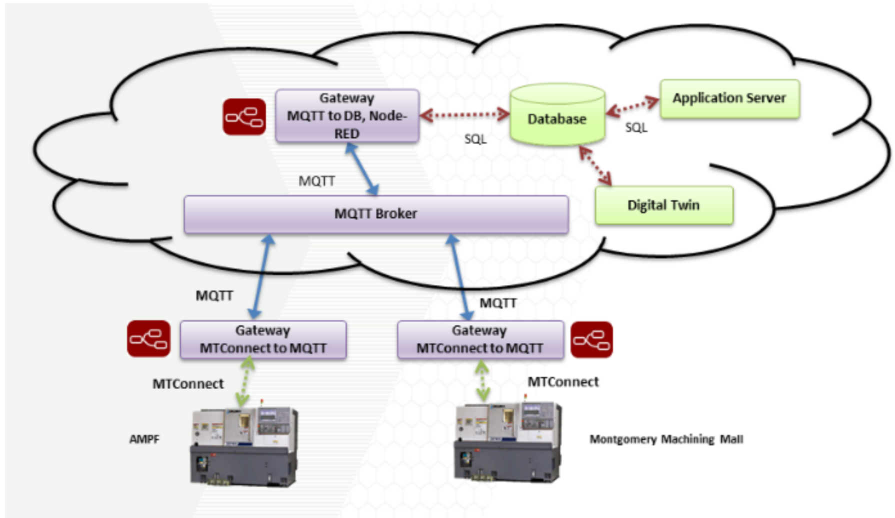

Figure 1 – Georgia Institute of Technology digital manufacturing architecture [19].

CHAPTER 3. USE CASES

Three common uses cases were selected for analysis to determine the ways in which Industry 4.0 technologies could benefit their operations. Our selected use cases were inspired by the needs of three different environments associated with manufacturing processes. The first use case is a small-scale machine shop, or "Job shop", where quantities of discrete parts made range from 1 to 10,000. This shop's capabilities include CNC machining, metal forging equipment, and other equipment for discrete processes. The second use case is paper mill for continuous manufacturing of pulp and paper products. This shop's capabilities include paper machines with high-viscosity pumps, revolving pulp presses and dryers, a chemical distribution infrastructure. The third use case is an educational machine shop where students learn the fundamentals of prototyping and manufacturing processes. This shop's capabilities included small hand-held power tools, small raw material processing equipment such as band saws and grinders, manual mills and lathes, and CNC 3-axis mills.

3.1 Small Machine Shop

Our first use case, the small machine shop or "job shop", is a family owned business or small corporation that manufactures discrete parts between 1 and 10,000 in quantity. These parts are manufactured with both manual and Computer Numeric-Controlled (CNC) mills and lathes, collectively referred to as "CNC machines". Job shops (as well as larger manufacturing centers) rely on a value-added business model as they produce desired parts from raw materials. Profit is gained when the shop's cost to produce the part is less than the market value of the part. In this model, time efficiency and cost-reduction is of the utmost importance because it directly affects the profit gained by the company.

In many job shops, producing profit in a short-term time frame can be exceedingly difficult when common CNC machines of quality for small parts range from $30,000 - $500,000 in price. To recover the costs, job shops wish to keep the machine in operation at all times. When the machine is not in operation, or in a period of down time, revenue is lost through missed opportunity cost. Thus, Job Shops wish to minimize down time as much as possible. This illuminates a need for measuring a machine's overall usage.

Machine usage is one component of the Overall Equipment Effectiveness (OEE) measurement of a process[3]. OEE is a common industry standard of measurement to evaluate an individual machine or process, collection of machines, or the shop as a whole. OEE is calculated by considering the availability, performance, and quality of a process or machine.

3.2 Paper Factory

Our second use case, the paper factory, is a large-scale continuous manufacturing center. The paper factory has capability to produce pulp of varying viscosities and rolls of consumer paper products. While paper machines are extremely complex, we will focus on the conversion of pulp to large rolls of paper products for our study.

Consistent with the job shop and most manufacturing optimization, down time on any machine is to be avoided. While regular maintenance of the machine can be scheduled to minimize lost production time, unexpected shutdowns of the machine are costly. A common failure point in paper machines are bearings that support heated rollers, loosely referred to as dryer canisters. Sometimes greater than 10m in length and 2m in diameter, the heated rollers press and dry the pulp mixture to produce a continuous sheet of paper at nearly 30km per hour. Each of these rollers contain at least two bearings, one at each end of the cylinder. When the bearing begins to fail, more heat is generated, more energy is consumed to continue moving the dryer roll, and the roller vibrates with a different characteristic pattern.

3.3 Manufacturing Education

Figure 2 – The IDEA Lab at Georgia Tech used to instruct students in introductory design and fabrication methods. The IDEA Lab is an example of our manufacturing education use case.

The third and final use case in our study is a machine shop dedicated to education of prototyping and manufacturing methods. This machine shop can safely hold up to 50 students at any time and contains stock preparation machines such as a band saw and grinder, hand power tools, manual mills and lathes, and CNC mills. Additionally, the shop contains basic prototyping tools such as a 75watt laser cutter for wood and plastics as well as select Fused Deposition Modeling (FDM) 3D printers. An example educational shop, the IDEA lab, is presented in FIGURE. The IDEA lab is located at Georgia Institute of Technology and used as a collaborative space to instruct introductory design and fabrication techniques.

One of the most common ways in which the shop's equipment is used incorrectly is seen when students dangerously cut metal on vertical band saws with blades intended for wood. Wood blades have much larger teeth and fewer teeth per inch. These blades are extremely dangerous to use to cut metals because the larger teeth are designed to cut a thicker chip on every pass. While this is acceptable for woods and other relatively soft materials, wood blades can bury into metals and break individual teeth or the entire blade, mechanically jam the band saw drum, and create sharp projectiles. Improper use of this equipment is especially dangerous for the student operator. However, band saws are commonly used to cut metal when outfitted with appropriate blades. These blades have much smaller teeth and more teeth per inch to remove thin chips of metal. The difference between cutting metal with a wood blade and with a metal blade can be easily distinguished by the audible sound and vibrations from the machine. These signature patterns can be classified to determine proper or improper use of the machine.

Additionally, our machine shop under consideration supports a class of nearly 300 students. It frequently becomes full on a periodic schedule, especially leading up to due dates for prototypes that the students are required to make. However, the machine shop can be almost empty at other times during the day. Students currently have no way of knowing the status of the machine shop without visiting it in person. Similar to the job shop calculation of OEE, a way to measure the real-time usage of the educational shop's machines is desired. Over time, historical usage can be used to inform preparations for predicted high-usage periods.

CHAPTER 4. DESIGN OBJECTIVES

Understanding the health and diagnostics of manufacturing equipment is vital to efficient and consistent operation of a manufacturing facility. While many solutions have been developed to wireless monitor these machines, these sensors are very costly, specific in nature, and often do not provable flexibility in configuration to extend battery life or change the quality of measurement.

A need exists to produce a low-cost, highly flexible, and robust sensor platform to rapidly deploy Industry 4.0 technologies. The Wireless Accelerometer Sensor Platform (WASP) was created as a modular Internet-of-Things for Manufacturing device (IoT4MFG) to fill this need.

4.1 Design Requirements

Our design requirements for the WASP were driven by the needs presented in each of these three use cases. Individual design requirements from each use case were cross referenced against the other two use cases to find similarities. The design requirements and sources are summarized in Table 1. One of the most valuable insights gained from analyzing three separate applications is the need for modularity within the sensor capabilities of the WASP platform. While we are designing a product to meet the needs of each of the three use cases presented above, the sensor pack has the opportunity to become a platform to fill future needs of other operations not specified in this paper. This is achieved by our strategic design choices of supported communication protocols, sensor interfaces, and careful planning of modular and expandable mechanical connections.

The most important engineering specifications common to each use case were found to be the selectable accelerometer sensitivity, the supported communication protocols, and the contact surface area of the WASP sensor pack. The sensor's contact surface area is also a major design consideration because it relates both to the attachment force of the sensor and the wireless charging capabilities. With a greater surface area, more magnets can be used to provide a greater contact force and a more secure attachment to the machine. Additionally, the greater surface area allows for a larger inductive charging coil to be used in the sensor pack's base. However, the larger contact surface area inherently increases the overall size and volume of the device, which negatively affects the sensor's ability to be placed anywhere on a machine. A balance must be found between the contact surface area for increased attachment force and minimal volume to keep the sensor pack as small as possible.

Table 1 – List of Design Requirements and sources from three use cases. These design requirements will drive the engineering requirements to influence the design and functionality of the WASP.

Design Requirement	Source
Machine usage	Job Shop
Spindle and bearing analytics	Job Shop / Paper Factory
Supports multiple sensors	Job Shop
Waterproof	Job Shop
Compatible with GT Digital Architecture	Job Shop
Wireless communication	Paper Factory
Wireless charging	Paper Factory
Wireless placement	Paper Factory
Identification of bearing elements	Paper Factory
Material identification	Education Shop
Machine availability	Education Shop
Easy to use	Education Shop

4.2 Usage Requirements

One of the most important factors in the adoption and success of new machining technology is ease of use, and flexibility in application. Particularly in the manufacturing industry, where change in capital and infrastructure is extremely costly, success in adoption rests on the ease of implementation. This is clearly evident in our use cases where machinists do not have the time or desire to continually adjust, fix, or debug auxiliary monitoring equipment that does not directly impact their productivity in terms of part production. Any auxiliary technology must be very easy to set up and require minimal maintenance.

Furthermore, the sensors must have an interface through which the user can quickly verify proper installation and operation of the sensors. Many commercially available sensors such as the Fluke Wireless Accelerometer [4] and Bluvision Beacon [10] must be permanently placed on the machine and are hard to immediately verify strong reception of vibration. Additionally, conduction of vibration dramatically varies in different locations on the machine. Depending on the machine's design, sheet metal may be rigidly or non-rigidly attached to the structural components that resist loading. Conduction of vibration may be very strong in one particular location of the machine's covering, but very weak just a few centimeters away.

Our solution must include a method through which the user can quickly verify proper placement on the machine to measure (and hopefully improve) vibration reception. In order to improve vibration reception, the user must be able to readily adjust the position of the sensor, identifying the need for a non-permanent or semi-permanent fastening method. Standard fastening methods such as epoxies, industrial grade double-sided tape, or bolting hardware will not suffice.

CHAPTER 5. MECHANICAL DESIGN

Two versions of the Wireless Accelerometer Sensor Platform were designed and implemented. Each of these designed were explored to better understand the needs and requirements for a mass-manufactured product.

The first, Version A, was designed and implemented to explore the nuances of working with a plastic-housed sensor pack. Version A was also more rudimentary in electronic operation, laying the groundwork for wireless communication and basic data acquisition. This provided fundamental operation which could in turn be revised and expanded in a further iteration. The second iteration, Version B, was implemented as a more robust and rugged sensor pack, designed to withstand a much harsher manufacturing environment. Additionally, slight design changes were implemented from the knowledge gained in fabricating and testing Version A. The electronic capabilities of the sensor pack were increased, creating a more flexible and operationally redundant product. Each design provided independent value in the overall design of the WASP sensor pack from different manufacturing and applications perspectives, and both are included for analysis.

5.1 Version A

5.1.1 Design Goals

The main goals in designing Version A were to better understand the fit and placement of the WASP components. Many of the sensors included in the design are taken as packaged hobby-grade components. They may not be true to dimensional drawing tolerances, and there may also be subtle changes in their layout and interoperability that was not described in the technical documents. We also aimed to test a retaining mechanism for holding the WASP Li-Po battery. In terms of mechanical assembly, we chose to test two types of fastening mechanisms, interference fits and threaded hardware. Finally, Version A was intended to test the thicknesses and iterations relating to magnets included in the design.

5.1.2 Overall Design

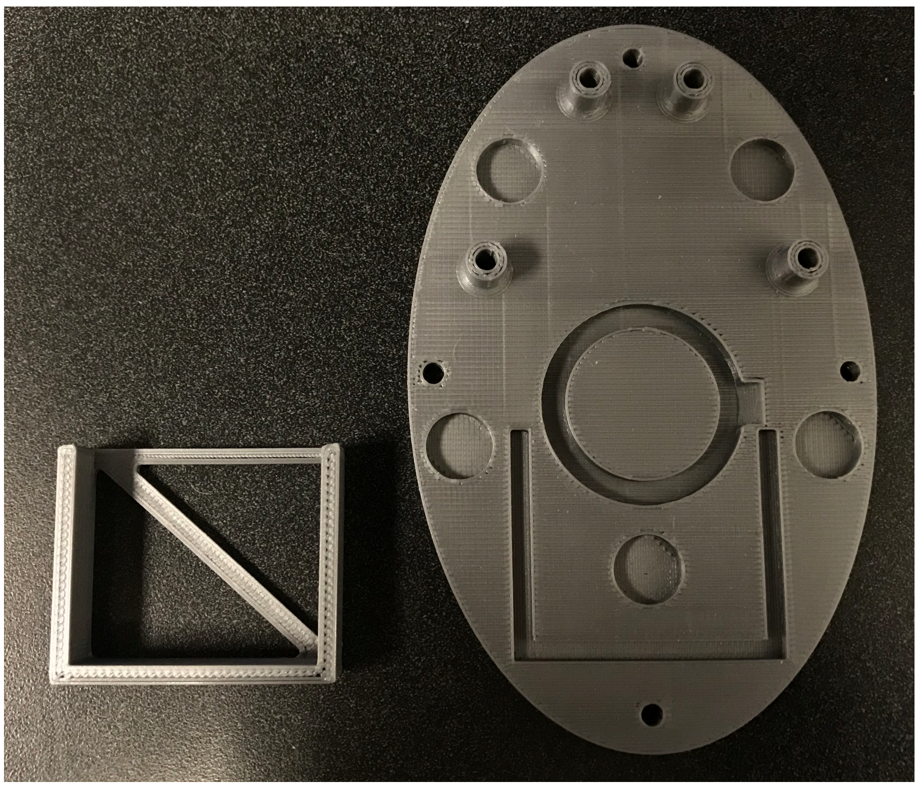

Figure 3 – [Right] Version A baseplate 3D printed with interference fit locations for magnets, inductive coil, and heat-set threaded inserts. Slip fit pattern for battery gate. [Left] 3D printed battery gate designed to retain battery on Baseplate.

The mechanical design for Version A is displayed in Figure 3. The baseplate provides the foundation for all other components, and subsections of the baseplate are discussed below.

5.1.3 Baseplate

The baseplate is arguably the most critical mechanical component of the assembly. The baseplate provides the mechanical support to which all other components are fastened. There are three main requirements that the baseplate must meet; providing a rigid framework to which all other internal components can be fastened with a minimum number of parts, providing a method of attachment for the sensor pack to the machine, and protecting the sensor components from the manufacturing environment.

The baseplate, displayed in Figure 3, must provide a framework for all other mechanical components such as the inductive charging coil, supporting electronics, Lithium-polymer (Li-Po) rechargeable battery, and magnets for magnetically mounting the sensor pack to the desired machine. The majority of components were fastened with permanent interference fits to minimize the number of parts needed for assembly. Exceptions occur where components would need to be periodically removed and re-assembled.

5.1.4 Heat-Set Threaded Inserts

Additionally, some components of the WASP sensor pack must be periodically removed for maintenance and inspection. The waterproof top cover and custom electronics printed circuit board (PCB) are two such components. Single use fastening methods such as locking tabs or press fit interferences are not acceptable for this purpose.

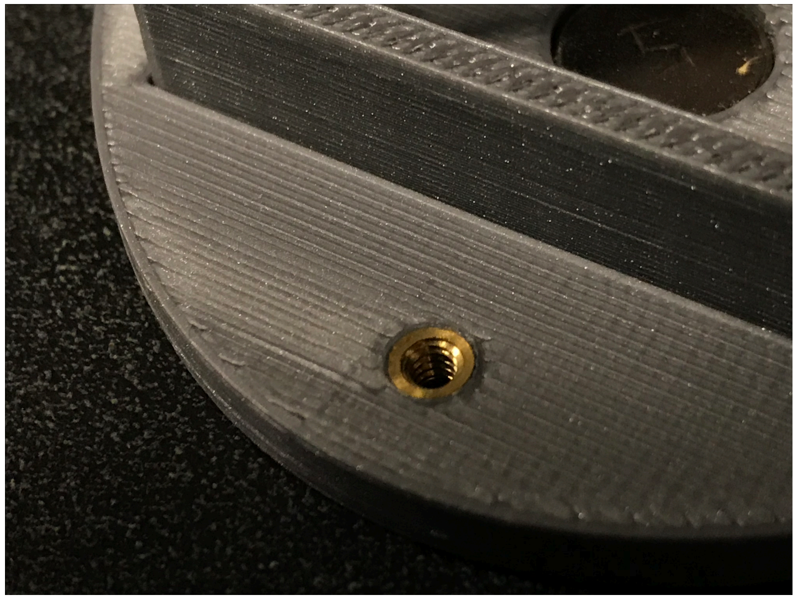

Figure 4 – Heat-set threaded inserts in 3D printed baseplate to provide reliable assembly and disassembly of baseplate components.

Instead, small machine bolts were chosen to fasten the components. One of the most difficult challenges with using bolts in a plastic medium is manufacturing strong threads. If the minor diameter of the bolt is manufactured, the bolt can typically self-cut threads to the correct major diameter the first time it is inserted. However, these threads are only reliable for a handful of cycles before the much harder metal bolt wears them down. While this method may be acceptable for single or low-use components, the WASP threads must be reliable across multiple assembly cycles. To achieve this, threaded brass inserts were chosen, displayed in Figure 4. A slight interference diameter was designed such that the brass insert could be heated and plunged into the hole. This method will also be sufficient for mass manufacturing as the inserts can be placed in the injection molding molds.

5.1.5 Magnetic mounting

Magnetic mounting was chosen to semi-permanently attach the WASP sensor pack to the desired machine. This method is capable of achieving the desired engineering requirements of a minimum 5 lbs. of attachment force. The realized force of attachment (or in this case, force of attraction) is exponentially related to the distance between the magnet and the ferrous material. The force of attraction/attachment also depends on the magnet material, the diameter of the magnet, and the thickness of the magnet.

Aside from the press fit diameters, one of the most critical dimensions of the sensor pack baseplate is the thickness of material between both the magnets and the inductive charging coil, and the bottom surface of the baseplate. Achieving the correct thickness is extremely important for two reasons. Mentioned above, we wish to maximize the force of attraction between the magnets and the ferrous material to which the WASP sensor pack will be mounted. An extremely thin layer of plastic is desirable to minimize this distance. However, we do not wish the plastic to fracture or break when the users pulls the sensor off the machine. A layer of plastic that is too thin will provide a mechanical failure point. Additionally, we wish to minimize the distance between the sensor's receiver inductive charging coil and the powered transmitter inductive charging coil. While this thickness does not experience a load of the same order of magnitude as the magnets, there is still a considerable concern of puncturing the plastic layer between the receiving inductive coil. Excluding the raised posts to hold the PCB, the overall thickness of the baseplate is 5mm. A minimum thickness of 1.5mm was chosen for the inset magnet wells to achieve enough force to magnetically mount the sensor to a machine while still retaining enough mechanical strength to prevent fracture when removing the sensor. Since the wireless charging coil does not experience as high a load, a minimum distance of 1mm was chosen for the coil's locating inset well.

5.1.6 Inductive Coil

A slip fit for the inductive coil was included in the design to facilitate convenient charging of the device. The electronic operation is discussed later in Electrical Design. The inductive coil included in the baseplate design is one of two parts needed to wirelessly charge the WASP. The first part, a transmission coil with supporting circuitry is contained in a home base, not displayed. The second coil, a receiving coil, must be placed as close as possible to the transmitting coil. Similar to the magnetic force, the effectiveness and efficiency of power transmission between the coils is related to the distance between them. A minimum thickness of 1mm was chosen between the face of the coil seat and the bottom face of the WASP baseplate. This thickness was chosen slightly less than the magnet seat thickness because the coil does not need to support any mechanical load. In reality, a much thinner part could be created, approximately 0.5mm or less, but the consistency and reliability in manufacturing a wall of that thickness may decrease.

5.1.7 Rechargeable Battery

Although the attachment magnets and inductive charging coil (discussed below) were press fit into the sensor pack baseplate, a retaining cage for the battery was designed to slip fit in to a groove on the sensor base plate.

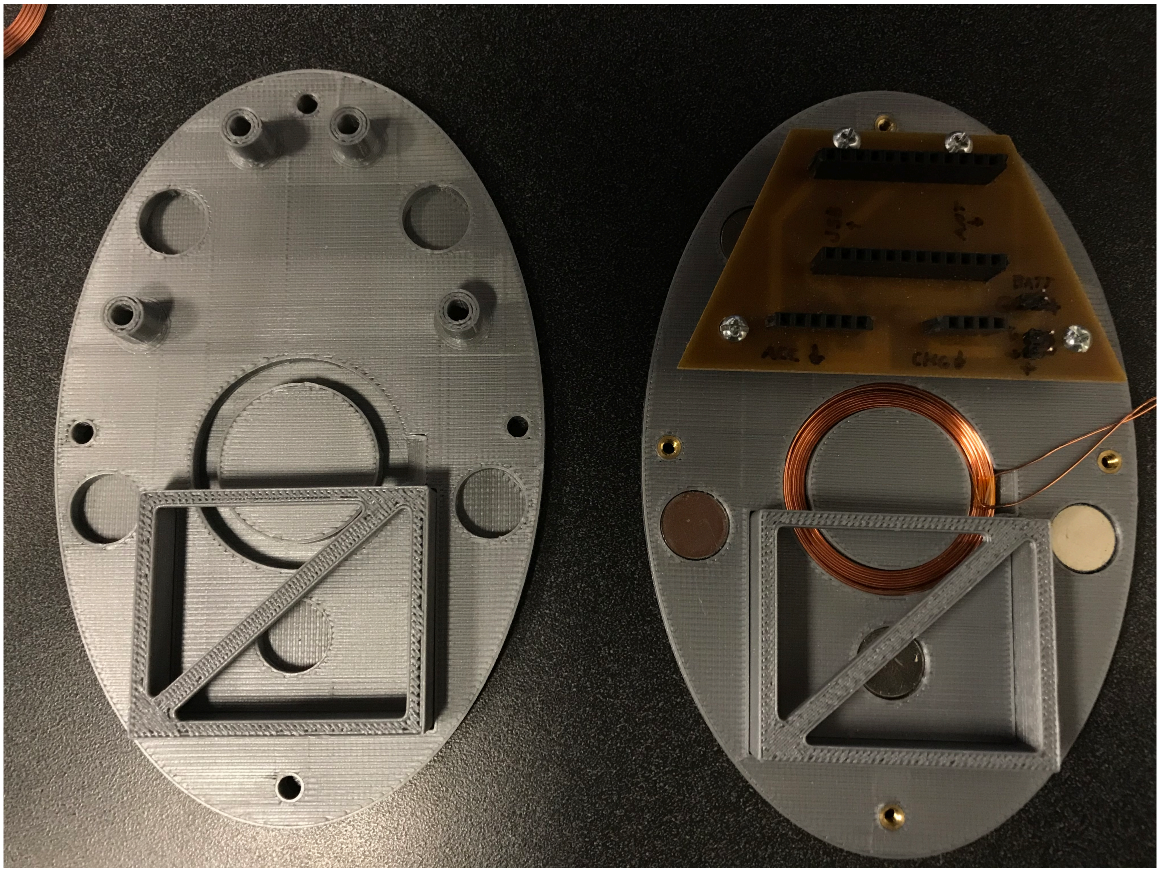

Figure 5 – [Left] WASP baseplate assembly with battery gate installed. [Right] WASP baseplate assembly with heat-set threaded inserts, inductive coil, magnets, and custom printed circuit board (PCB).

A slip fit was chosen for this assembly process for the thin, light-weight retaining cage to because cracks and fractures were likely to occur if a press fit was attempted with a small plastic part. The retaining cage is glued in the final assembly to prevent it detaching from the baseplate. The assembled sensor pack with battery gate is displayed in Figure 5.

5.1.7 Mass-Manufacturing Methods

Finally, the sensor baseplate was designed with large scale manufacturing methods in mind. Each part of the mechanical baseplate and supporting parts were designed according to standard injection molding principles. Features such as overhangs, acute angles, or parts requiring a complex-action mold were not used in the design. Additionally, all inset walls can be “drafted”, or given a slight obtuse angle above the normal 90deg corner, without affecting the functionality of the mechanical design. Furthermore, the inset wells for magnets and the inductive charging coil provide a convenient and hidden location to place ejection pins.

5.2 Version B

5.2.1 Design Goals

Version B was designed as a rugged, robust, and waterproof version of the Wireless Accelerometer Sensor Platform (WASP). While the plastic implementation is convenient for injection molding and mass manufacturing, polymers can degrade in hot or otherwise caustic environments. A more rugged framework is required to withstand some harsher manufacturing environments. Additionally, waterproofing is required for the sensor to operate inside the chamber of some manufacturing machines. This is especially important in CNC operations where a stream of coolant is flooded over the part. The sensor must not be susceptible to splashes or high humidity.

Version A of the WASP sensor pack was implemented following the process outlined in Version A Fabrication section below, and observations from its implementation were compiled to inform design changes in Version B. These design revisions reduced the overall surface area of the baseplate, reduced the number of manufactured parts required, and refined some mechanical interfaces inside the sensor pack. Version B is a result of both the need for a rugged WASP and from iterative improvements from Version A.

5.2.2 Overall Design

Figure 6 – The Wireless Accelerometer Sensor Platform (WASP) assembled with waterproof cover.

The overall Version B assembly is presented in Figure 7 with the top cover protecting the baseplate and electronic components. Three LED indicators were included on the top of the cover to provide basic feedback to the used and reflect the state and health of the sensor packs.

5.2.3 Baseplate

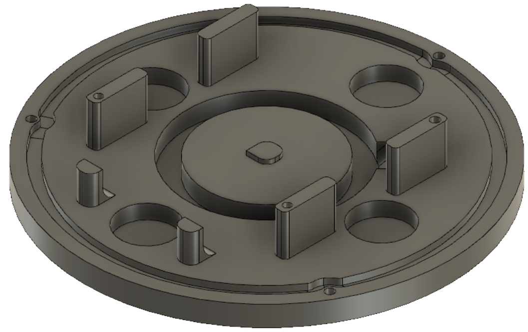

Figure 7 – The WASP baseplate, with gates to retain the battery and provide mounting points for the circuit board. Interference fit holes were left for magnets and inductive charging coil.

The base plate for Version B included design revisions influenced by observations from fabricating Version A. By optimizing the location and placement of components, the overall surface area was reduced by 38% from Version A.

The battery gate component was removed in Version B. Instead, locating retainers were design to serve both as a locating mechanism for the battery as well as support fixturing to which the custom printed circuit board is mounted. These retaining supports were slightly oversized to account for potential swelling of the battery over it’s lifetime.

5.2.4 Waterproofing

An O-ring sealing design was included in Version B to facilitate use of the sensor inside the operation chamber of manufacturing equipment, specifically to withstand splashes and partial submersion in cutting fluid of CNC machining equipment. An O-ring grove conforming to specifications presented by the Parker Hannafin Corporation [11] was added to the base plate. A 78mm ID O-ring was added to form a seal between the baseplate and the top cover.

Part of the O-ring seat was designed to slightly maneuver around slip fit mounting holes used to fasten the baseplate to the cover. These holes must remain outside the seal of the O-ring. However, we also wish the outer profile of the baseplate to remain circular, without small protrusions extending for the slip-fit holes. Though changing the circular shape of the O-ring seat is not acceptable for most pressurized applications, we carefully designed the circumference of the O-ring seat to match a known O-ring specification, ensuring that a proper face seal would form.

5.2.5 Fastening Methods

The battery of the sensor pack was designed to be constrained both by the retaining gates, discussed in Version A Baseplate below, and by the PCB mounted to the top of the retaining gates displayed in Figure 7. Blind holes in the battery gates were tapped with M2 x 0.4 threads to mount the custom PCB to the baseplate and retain the battery. M2 mounting and fastening hardware was consistently used throughout the design, eliminating the need for multiple threading processes or non-uniform fastening hardware.

CHAPTER 6. ELECTRICAL DESIGN

6.1 Introduction

Electrical design decisions were similarly driven by tradeoffs identified through evaluation of design requirements. The most important engineering requirements identified include choice of supported communication protocols for internal communication with sensors and other components, as well as external communication with the greater internet or local area network. Additionally, selectable accelerometer sensitivities to achieve appropriate data acquisition for each of the three use cases and the overall battery life of the WASP sensor platform were important requirements.

6.2 Processing Evaluations

An appropriate microcontroller development platform must be strategically selected. Careful consideration of the development platform's capabilities and features significantly affects the types of sensors that can be supported. Additionally, the choice of microcontroller used in the development platform heavily influences the supported communication protocols, addressing another significant engineering requirement. Furthermore, the features contained in the development platform, and whether or not those features are necessary for this application dramatically affects overall power consumption of the WASP sensor platform, addressing a third important requirement. While these three requirements may seem moderately independent, the successful achievement of each one fundamentally relies on our initial choice of microcontroller.

Three microcontroller development boards were considered for selection; Arduino Nano, BeagleBone Black, and Particle Photon.

6.2.1 Arduino Nano

The Arduino Nano [12] development board was considered particularly for its low power consumption and ease of programming. Running on an ATmega 328 microcontroller, the Nano achieves the internal communication specifications for transfer of data between components. However, external communication boards are needed for Wi-Fi and Bluetooth Low-Energy (BLE) communication. Additionally, the Nano provides convenient programming access to General Purpose In/Out pins for measurement and control of analog and digital signals. A potential challenge with the Nano is found with its lower computational abilities. This has potential to be problematic if the users require onsite spindle analytics and material identification capabilities. A tradeoff with power consumption is required for increased computational power.

6.2.2 BeagleBone Black

The BeagleBone Black (BBB) development board [13] was considered because of its high computational power and built-in Wi-Fi communication capabilities. The BBB contains an impressive array of communication protocols and is powered by a Linux-based computational platform. However, the BBB requires a significant increase in power to support these features when compared with other microcontrollers. A battery life of 7 days would be very difficult to achieve.

6.2.3 Particle Photon

The Particle Photon [14] was considered because of its combination of supported communication protocols and moderate computational capabilities. The Photon contains built-in Wi-Fi communication capabilities and supports our required SPI and I2C internal communication protocols. A battery life of 7 days would also be reasonably achievable with this development board. Additionally, the Photon supports over-the-air programming, allowing analytic functionality to be upgraded quickly and remotely. However, the Particle Photon contains an STM32F205 microcontroller, which moderately satisfied our computational requirements. This development board would also require an additional board for BLE communication.

The Particle Photon development board was selected for use in this product due to the combination of supported communication protocols, moderate computational capabilities, and low power consumption. While the Particle Photon consumes more power than the Arduino Nano due to the Photon's built-in Wi-Fi communication capabilities, volume saved without the need for a Wi-Fi communication board can be traded for a Li-Po battery to achieve the desired engineering requirement of a 7-day battery life. Additionally, the over-the-air programming capability provides an added benefit to the user, allowing for rapid changes to the computational methods employed depending on the user's needs.

Mentioned above, the Particle Photon supports a range of internal and external communication protocols. One of its greatest strength is the capability to handle both analog and digital sensors. The Photon contains 6 pins that are wired to an Analog-to-Digital Converter (ADC), allowing for the measurement of analog voltage sensors. This is particularly useful for high frequency vibration measurements as the user can rely on the Photon's high sample rate ADC to measure an analog accelerometer, instead of the lower quality ADCs that usually built in to digital accelerometers. However, at times it is much more advantageous to use a digital sensor, and the Particle Photon also has 8 digital inputs to handle this as well. The photon's diverse capabilities allow it to act as a platform to handle a variety of sensors. Temperature readings, humidity detection, and light measurements are all supported with this choice of microcontroller. Additionally, the Photon supports I2C and SPI communication for internal data transfer between digital sensors and the Photon's microcontroller. This allows our product to achieve the engineering requirement of sensor modularity.

6.3 Version A

6.3.1 Custom Printed Circuit Board (PCB)

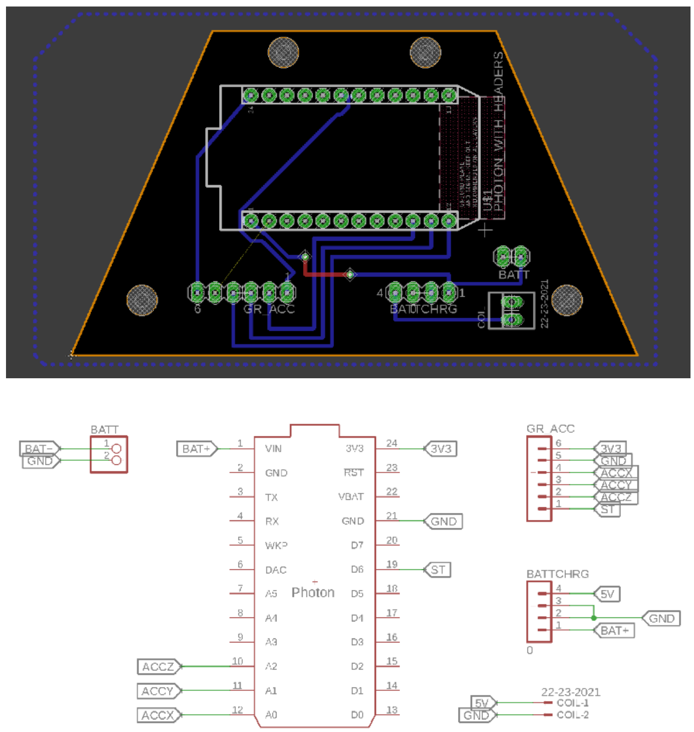

Figure 8 – Autodesk EAGLE printed circuit board design files. [Top] Board layout design. [Bottom] Component connection diagram.

A custom printed circuit board was designed for the WASP to coordinate power and data acquisition signals. The design for Version A’s custom PCB is displayed in Figure 8.

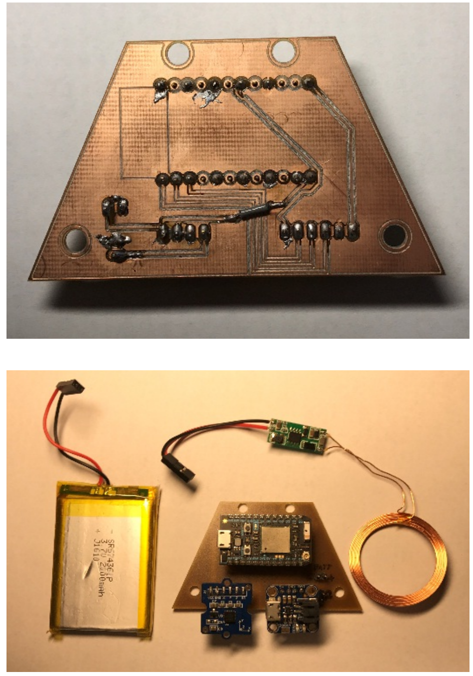

Figure 9 – Top and bottom views of custom printed circuit board designed for WASP. A 2200mAh battery and an inductive charging coil were integrated into the baseplate design.

6.3.2 Wi-Fi communication

The initial external communication method included in the WASP design was Wi-Fi technology, providing the ability for the WASP to communicate to a local or external network. The Particle Photon was chosen in large part due to the ease in which Wi-Fi communication could be controlled. Furthermore, the Photon's Wi-Fi capability includes the ability to update the device firmware and configuration over-the-air (OTA updates), allowing the user to rapidly deploy new code without being present with the sensor. Finally, Wi-Fi communication allows for compatibility with GT's digital architecture. Data from the sensor can easily be sent to the MQTT message broker and stored in a database for real-time or post-production analysis.

6.3.3 Inductive charging

A wireless charging system was added to the electric design to easily and conveniently charge the WASP. Wireless charging systems consist of paired inductive coils. One “transmitting” coil is connected to a power supply, usually held in a home base plugged into a standard 120V AC supply. A second “receiving” coil is included in the device to convert the inductive current into supported voltage standard to be used by the device.

6.3.4 Analog and Digital Accelerometers

Two accelerometers were included in the WASP, an analog 3-axis accelerometer and a digital 3-axis accelerometer. Both accelerometers were included to serve different purposes in machine monitoring operations. The accelerometers may also be used independently for data collection, or even as a fail-safe checking system to determine if one of the accelerometers has degraded or malfunctioned.

The digital accelerometer is intended to serve as a passive shock monitoring system. A digital accelerometer was chosen because of its interrupt triggering capability. The battery life of the WASP is directly related to the usage and sensor sampling scheme. With the digital accelerometer, we can configure the Particle Photon to sleep in an extremely low power consumption state during the majority of its uptime but wake if the digital accelerometer passively triggers an interrupt. This allows the Particle photon to passively monitor manufacturing equipment for crash detection and other high acceleration or high shock events.

The analog accelerometer was included to take quality vibration measurements at a higher frequency than is possible with the digital accelerometer. Most digital accelerometers include their own analog-to-digital converter (ADC). This ADC is the limiting factor in the sampling rate of the sensor. However, the Particle Photon's built-in ADC can sample at a frequency up to 20 kHz. This far exceeds the capability of most low-cost digital accelerometers. An analog accelerometer was included to be sampled by the Particle Photon to measure higher frequency vibration data. These

6.4 Version B

6.4.1 Common Header Specification

A Common electrical header interface was developed to add modularity to the sensor pack. Displayed in Figure 10, common connections were established so that other sensors and supporting components can be added to the board at a future time, without interfering with current sensors. The headers are designed to be stackable, providing a method of rapidly expanding the sensor pack's capabilities. Additional PCBs, or "Jackets", can be stacked on top of the current design to include additional capabilities.

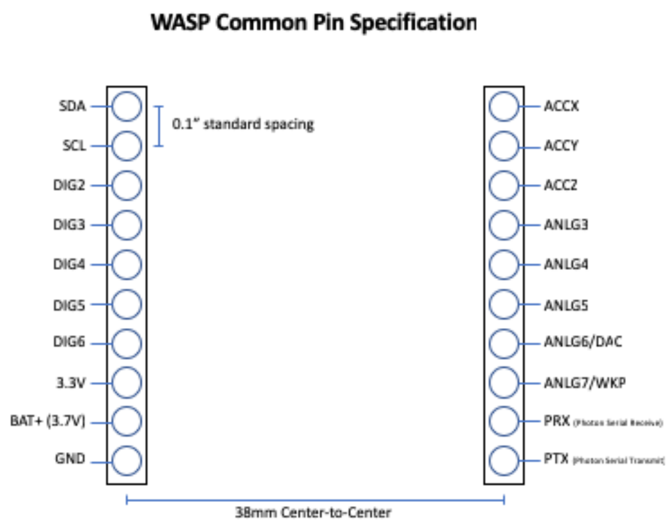

Figure 10 – WASP Common Pin Specification, top down view. Common internal communication protocols are defined on specific pins. Configurable pins are provided for sensor expansion.

The left side of the header specification provides three pins for power connections. Three pins are reserved for and ground connection, 3.3V connection, and a 3.7V battery connection. Additionally, two pins are reserved for a data connection (SDA) and a timing/clock connection (SCL) conforming to I2C. The remaining digital pins are reserved for SPI communication, or general digital input/output pins as required by sensors.

The right side of the header specification provides analog connections to sensors and supporting components. Two pins are reserved for Serial communication with the Adafruit Flora Bluetooth Low-Energy module. Three pins are also reserved for measurements of the analog accelerometer that is standard on each WASP sensor pack. The remaining 5 pins are configurable for general analog input/output operations.

6.4.2 Standard Jackets

The WASP is designed to always include two standard jackets; a lower power and accelerometer jacket, and an upper communication jacket. While the communication jacket does not necessarily need to be immediately above the power board (it may be advantageous to keep the communication jacket at the top of the stack) the power jacket must remain as the bottom board so the stack can be mounted to the baseplate. These two jackets are displayed installed on the sensor pack baseplate in Figure 11, and the EAGLE circuit design for the power board is presented in Figure 12.

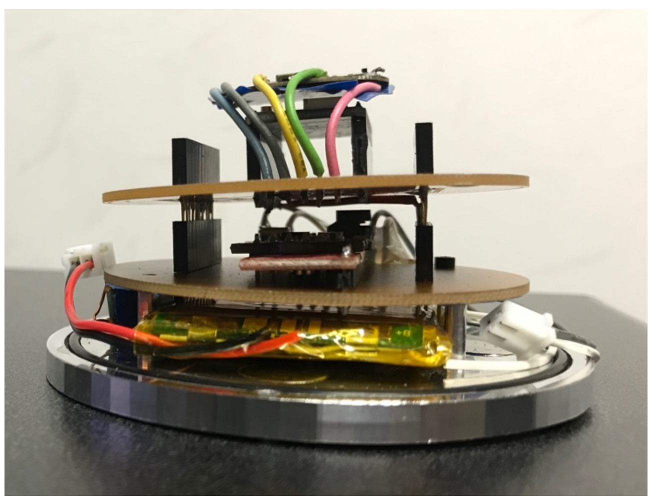

Figure 11 – WASP assembled with two jackets. Bottom to Top: Base plate with magnets and inductive coil; Battery resting between retention gate; Power jacket with analog and digital accelerometers; Communication jacket with particle photon and Bluefruit[1] BLE module.

The power jacket coordinates power transmission between the wireless charging circuit, the battery changer, and the common electrical interface. An inductive charging coil is used to receive power from the matching transmission coil wired to a power supply. It produces a 5V supply with up to 250mA of current. This input power is routed to the battery charger, which manages the voltage level of the Li-Po battery. The Battery's 3.7V supply is routed to the pin left pin connections, providing supply power to the Particle Photon on the communication jacket. In turn, the Particle Photon provides a 3.3V supply with a maximum 100mA current to supporting sensors.

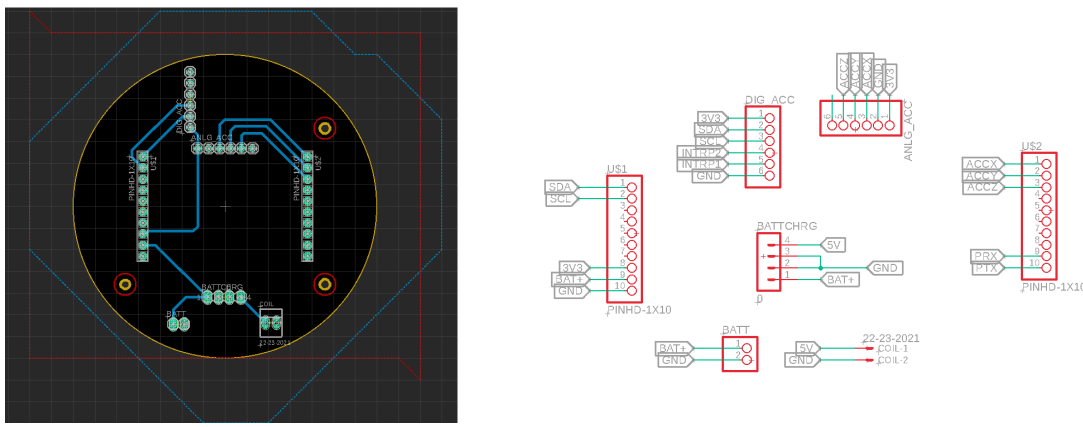

Figure 12 – EAGLE printed circuit board design for Power Jacket containing battery charger, analog accelerometer, digital accelerometer, and inductive coil input.

The power jacket also includes a digital accelerometer and an analog accelerometer. The digital accelerometer communicated with the Particle Photon via I2C protocol. The analog accelerometer is routed to the corresponding analog input/output pins to be sampled by the Particle Photon's analog-digital-convertor (ADC). Both accelerometers were included in the design to simultaneously provide high quality vibration measurements from the analog accelerometer, and interrupt capable shock detection from the digital accelerometer. Additionally, the redundant accelerometers allow for a fail-safe mechanism so that measurements of sensor can be compared against the other to determine sensors health or identify sensor deterioration.

The communication board consists of two components; a Particle Photon to control the system, sensors, and Wi-Fi communication, and the Adafruit Flora BLE module to communicate wirelessly with nearby devices. The Particle Photon provides the main computational support for the WASP sensor pack. Its microcontroller capabilities coordinate sensor communication while it's ADC measure analog inputs. Additionally, the Wi-Fi capability provides a means to wirelessly transmit data to cloud based analytic platforms. The Flora BLE module allows for near-field communication with mobile devices for setup, advanced diagnostic, and alert capabilities. Combining the two methods of communication prove useful to provide a highly flexible platform and achieve the design requirements for all three use cases.

6.4.3 Electrical Isolation and Grounding

One unintended consequence of Version B's rugged aluminium base is the electrical conductivity inherent in the metal case. Mounting the PCB and other components to the baseplate can be dangerous and potentially short the circuit if appropriate precautions are not taken. Additionally, inductive responses in the metal may adversely affect the performance of the sensors. This can be solved with insulating materials between the conductive layers, especially where electrical components come in contact with the aluminium housing. Electrical tape was used as a thin layer between components, and a more permanent plastic layer can be included in future revisions.

6.4.4 Bluetooth Low Energy

One of the most difficult challenges in developing any wireless product is balancing power consumption with function. Typically, increasing the functionality or computational capability of a product also increases its power consumption. Additionally, external communication protocols can significantly affect the computation needs of the processor in question. Although we have already chosen the microcontroller and processing capabilities for the WASP, the external communication protocol remains to be determined.

Epenstein (2015) [15] provided an analysis of power consumption for common communication protocols. It was clearly demonstrated that Wi-Fi communication required the greatest amount of power under normal operation conditions. However, Wi-Fi technology also provided the greatest data transfer rate as well.

The Particle Photon inherently contains the ability to communicate via Wi-Fi through its built-in transceiver, but this may not be the most efficient method of communication for a device where a battery life of days to weeks is desired. Epenstein also evaluated the Bluetooth Low-Energy (BLE) communication protocol and demonstrated a significant reduction in power consumption under normal operating conditions [15]. BLEs reduction in power consumption is accompanied by a reduction in data transfer rate and range of communication as well, but these performance characteristics would be acceptable in the WASP.

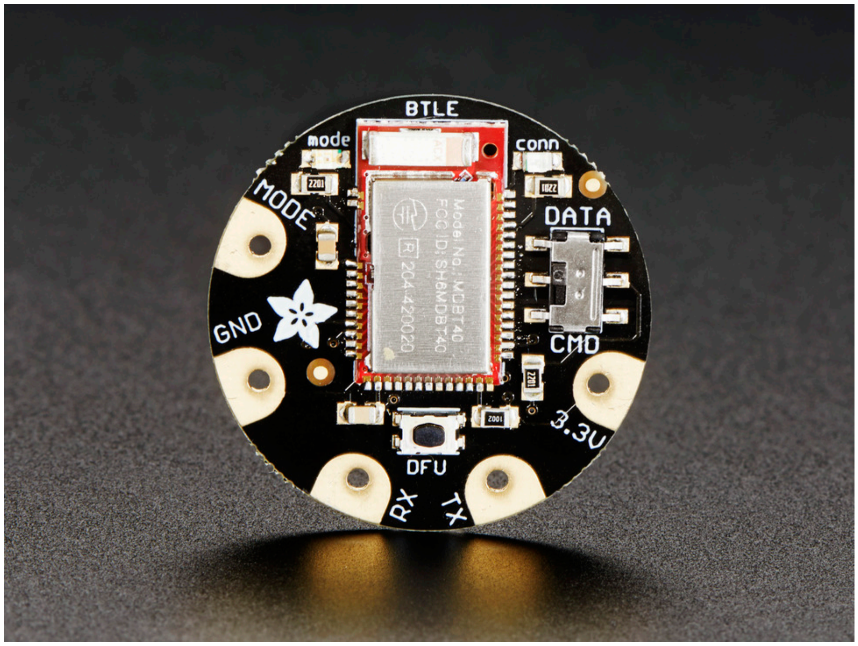

Figure 13 – Adafruit Flora Bluefruit LE module. [#] Communicates with the Particle Photon via hardware serial commands.

BLE was chosen as an additional method of communication to add to the WASP. By including BLE technology, the WASP can be configured to switch between Wi-Fi and BLE protocols depending on the function and data output required. BLE provides a convenient was to transmit smaller quantities of data over a shorter range if the high transfer rates of Wi-Fi are not required. Adafruit's Flora Bluefruit LE module [16], displayed in Figure 13 was included in the WASP electrical design on the communication jacket. The Bluefruit LE module internally communicates with the Particle Photon via hardware serial protocol and can also be configured through this serial connection as well.

CHAPTER 7. IMPLEMENTATION

7.1 Fabrication

7.1.1 Version A Fabrication

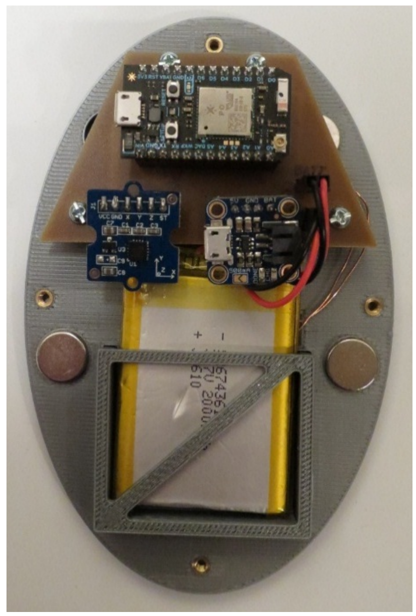

Figure 14 – Top view of WASP complete prototype.

The final assembly of Version A is displayed in Figure 14. One of the primary goals of creating this design was to better understand the nuances of working with a plastic baseplate. The WASP sensor pack was designed to be injection molded when mass manufactured. To simulate this process, Version A was 3D printed out of polylactic acid plastic (PLA) with an Afinia Fused Deposition Modelling (FDM) printer. The size of the baseplate was very close to the maximum base area in the X- and Y-axis on the 3D printer, and multiples iterations were required to obtain a successfully printed part.

Multiple iterations of the base plate were also required to achieve the correct interference-fit and slip-fit diameters. Final interference fit diameters were typically within 0.2mm of the nominal diameters.

Final assembly of the heat-set threaded inserts was achieved with a small soldering iron. The tip of the soldering iron was smaller than the inner diameter of the heat set insert. The insert was placed on the soldering iron, and the iron was plunged vertically into the undersides hole in the plastic part. It was difficult to keep the inserts perfectly vertical with our manual assembly method, but this could be optimized and controlled in a manufacturing setting.

7.1.2 Version B Fabrication

Version B was machined out of 6061-T6 aluminium on a 3-axis EMCO E350 CNC mill. Tools paths were created with AUTODESK Fusion 360 and run on a Siemens 828D controller. \\

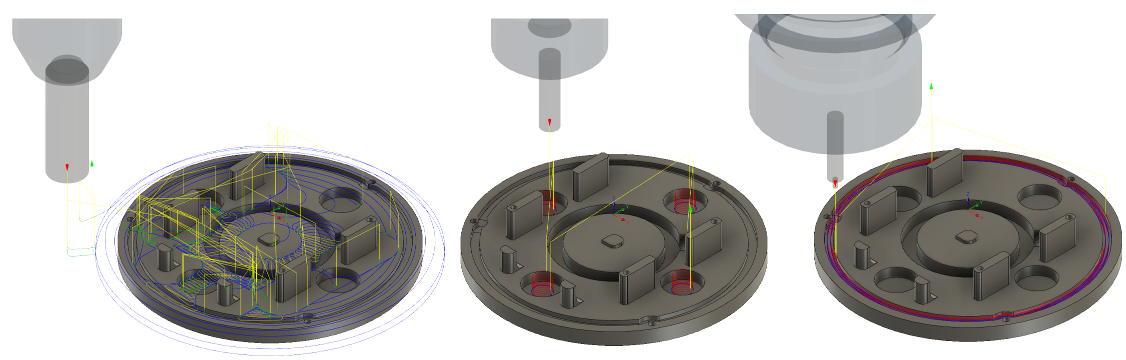

Figure 15 – CNC tool paths created with AUTODESK Fusion 360 to fabricate WASP Version B on an EMCO E350 CNC mill.

Three of the eight tool paths are displayed above in Figure 15.

The baseplate was machined out of 3 3/4in aluminium round stock. Both sides of a 1in thick slice of the round stock were faced, and parallel flats were milled on opposites sides of the stock to achieve greater clamping force, as displayed in Figure 16.

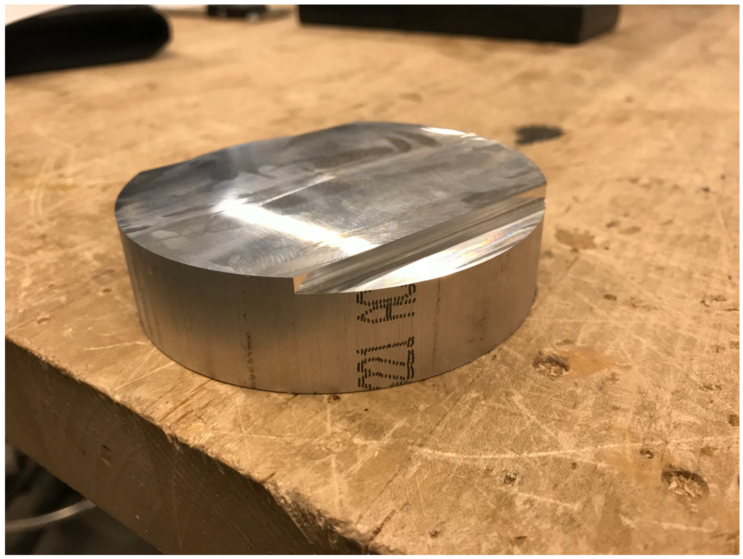

Figure 16 – 3 ¾ in round 6061-T6 aluminum stock for WASP Version B baseplate. A 1in thick slice was used as the initial stock, both sides were faced, and flats were milled on bottom side to achieve greater clamping force for top side machining operations.

Holes for PCB mounting and for assembling the WASP baseplate to the cover were center-drilled and drilled with the CNC mill. However, M2 threads were tapped by hand after the part was removed from the machine. After the top side of the WASP Version B baseplate was machined, the baseplate was flipped and the stock used to initially fixture the part was removed. Select images from the fabrication process are presented in Figure 17.

Figure 17 – WASP Version B fabrication on EMCO E350 3-axis CNC mill. [TL] Face mill and endmills used to machine the WASP baseplate. [TR] ½ in flat endmill used for rouging operations in adaptive toolpath. Coolant cleared for picture. [BL] 1/16 endmill used to machine O-ring seat for face seal against top cover. [BR] 1/16 in drill used for M2 thread initial hole.

7.1.3 Final assembly

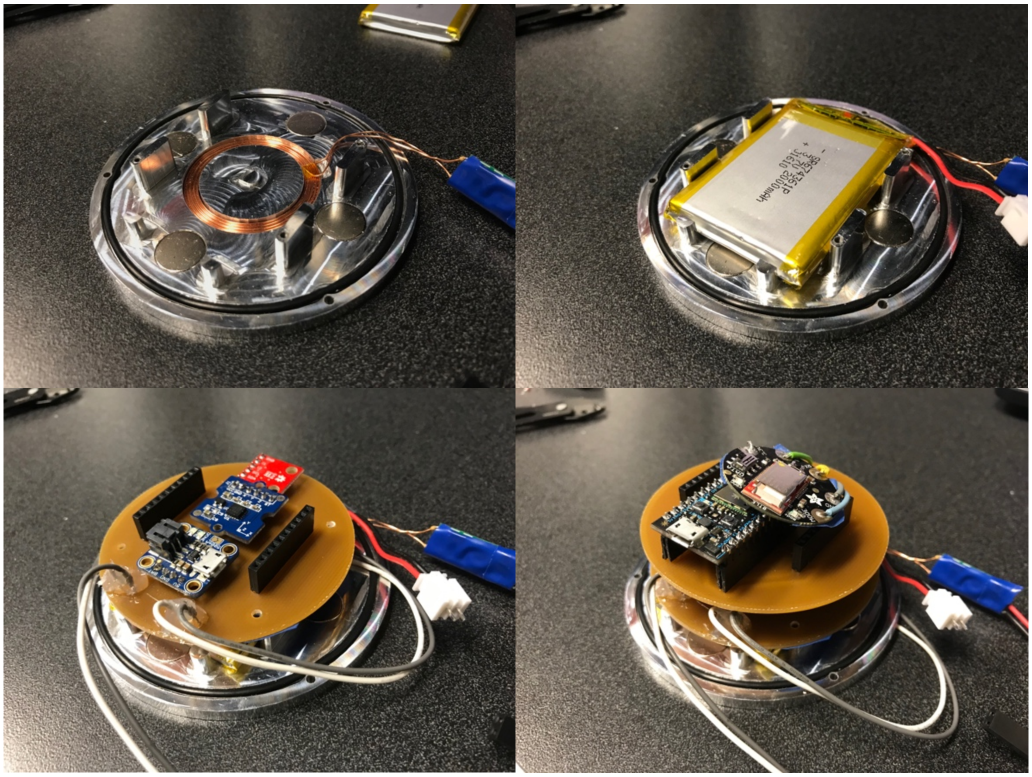

Figure 18 – WASP sensor pack in various stages of assembly. [TL] Baseplate with magnets and inductive coil. [TR] Baseplate with battery between gates. [BL] Power jacket mounted to baseplate. [BR] Communication jacket stacked on power board.

7.2 App development

One of our major Usage Requirements for the WASP is verification of proper placement on the machine through verification of successful vibration measurements. Commercial sensors often instruct the user to permanently mount the sensor to the machine, *before* verifying proper measurement of vibrations. The WASP semi-permanent magnetic mounting method allows users to mount and move the WASP sensor pack to find an location where sufficient vibrations can be measured. To determine the location, accelerometer measurements and feedback is needed so the user can adjust the position.

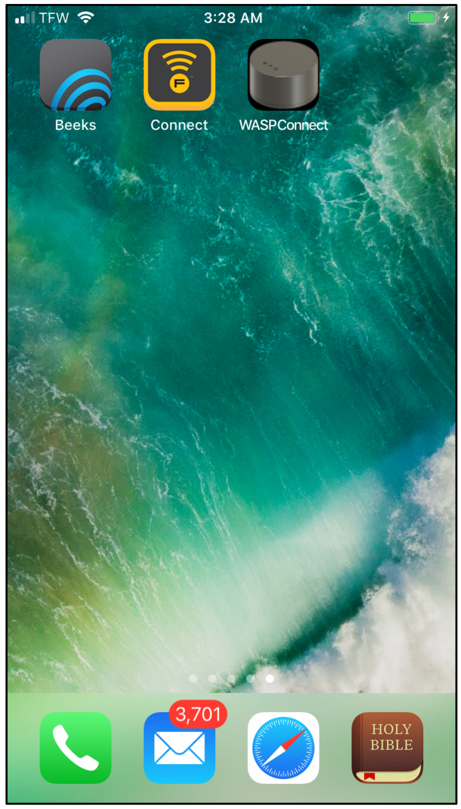

Figure 19 – WASP Connect, a mobile iOS app developed to assist the user in placing the WASP sensor pack on the machine by verifying and displaying accelerometer measurements in real time over Bluetooth LE communication protocol.

A mobile App was developed to address this need, displayed in Figure 19. The app was programmed in Swift [17] for Apple devices running iOS 7 and above. The app was heavily based on framework developed by Adafruit Industries Bluefruit LE Connect [18].Additional functionality was added to existing base framework. The app communicates with the WASP via Bluetooth Low Energy protocol through the Adafruit Flora Bluefruit LE module.

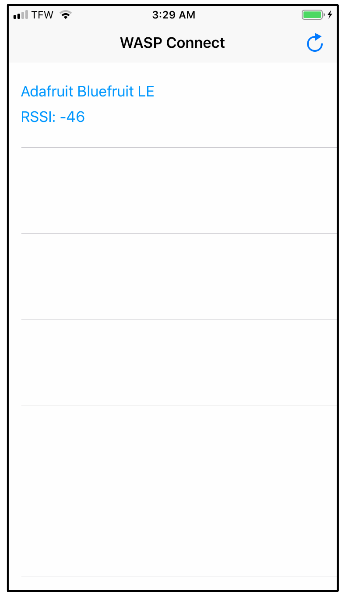

Figure 20 – Connection interface from base Adafruit Bluefruit LE Connect app, modified for WASP Connect app. Allows user to select which sensor to connect.

After the app loads, the initial home screen displays a list of Bluetooth devices who are advertising service characteristics with UART capability, displayed in Figure 20. This filters out any extraneous Bluetooth devices who are being used for other purposes (such as wireless headphones) or whose configurations do not match our intended uses (such as Bluetooth beacons.)

After selecting the desired WASP device, the app also allows direct communication and configuration of the Bluefruit LE module through a console. Commands can be sent to directly configure the BLE module or read raw data from the WASP sensors. This functionality provides users a quick way to read values from the sensor. Additionally, advanced users can diagnose the BLE module and reset configurations if maintenance is needed.

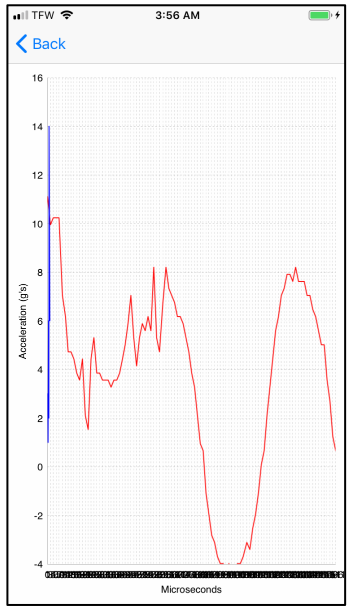

Figure 21 – Acceleration data measured by WASP and sent to the WASP Connect app via Bluetooth LE. Live view of the data allows the user to optimally place and move the WASP sensor pack on the machine.

The main functionality added to the base Adafruit open source app is the ability to see live sensor data plotted while the machine. One of the major problems identified with commercial sensors was the necessity to permanently mount the sensor to the machine in question before the sensor could be tested to evaluate vibration measurements. If the user did not place the sensor in a location with strong conduction of the machine's vibration, there is no recourse to move the sensor.

The WASP accounts for this functionality by providing live measurements from the sensor pack to the WASP connect app. Users can place the WASP on the machine with the magnetic mounting system ad instantly read data from the accelerometer, displayed

Figure 21, and shift the WASP to another location if desired to increase the vibration measurements. This also allows the user to turn or reorient the WASP axis to better measure the vibrations. A live feed functionality provides significant control to the user to better place the WASP on a machine and ensure successful measurement of acceleration and monitoring of the machine.

CHAPTER 8. SENSOR VERIFICATION

8.1 Introduction

One of the fundamental assumptions of our approach is that a low-cost sensors can provide analytic results of the same quality as more expensive commercial products. Industrial accelerometers such as the Fluke Vibration Sensor [4], discussed in Previous Work*,* cost approximately $250 per sensor unit and provide only limited access to raw data collected by the sensor. Furthermore, the sensors are very specific in the data they can collect and the type of sensor they can support. Anything outside the immediate purpose of the sensors requires costly custom applications from the company.

Our research rests on the assumptions that the same end result can be achieved through the use of low-cost components. However, the quality of data collection does not necessarily need to be the same degree of quality, if similar results can be achieved. To verify the accuracy of our assumption, we must investigate the quality of our sensors, and the information that can be discerned from the sensor's data. Even if the quality of data collected is not as good as high-end certified sensors, we may still be able to achieve the same results. Finally, if our low-cost components are not as good as certified counterparts, what information can be gathered from them?

8.2 Vibration Test Methodology

In order to measure the analog accelerometer included as a standard component on the WASP, the sensor pack was tested on a Bruel & Kjaer Type 4809 Vibration Exciter. The exciter, more commonly referred to as a "shaker machine", provides a controlled input

Figure 22 – Bruel & Kjaer Type 4809 Vibration Excited with frequency range of 10Hz to 20kHz and up to 60N output force.

to the sensor. The Type 4809 shaker can provide up to 60N of force in frequency ranges of 10Hz to 20kHz. The shaker machine is displayed in Figure 22.

Although the shaker machine provides a known input, the physical response to that input must be measured externally. At times, the shaker may be providing vibration of a given frequency, but the physical response may be dramatically larger or smaller depending on the resonance or anti-resonance response mode. Therefore, an external measurement system must be used to measure the physical response of the system. A Polytec OFV-505 Vibrometer matched with a Polytec OFV-5000 Vibrometer Controller was used to measure the velocity of the system during testing to measure the physical response.

In each test, white noise containing frequencies up to 10kHz were given to the shaker machine. The laser vibrometer was set to sample velocity at 20kHz, doubling the maximum expected frequency and eliminating effects of aliasing. Each noise bust was also repeated

10 times in every experiment, and the frequency response was averaged over the 10 repetitions.

Finally, knowing the vibration input and the physical system response, we are able to determine the accuracy of the accelerometer itself. During each test, a third data acquisition signal was used to measure the analog accelerometer output. The acceleration measurement can be compared to the change in velocity measured by the vibrometer, providing a measure of quality and accuracy of the low-cost accelerometer.

8.3 Vibration Test Setup

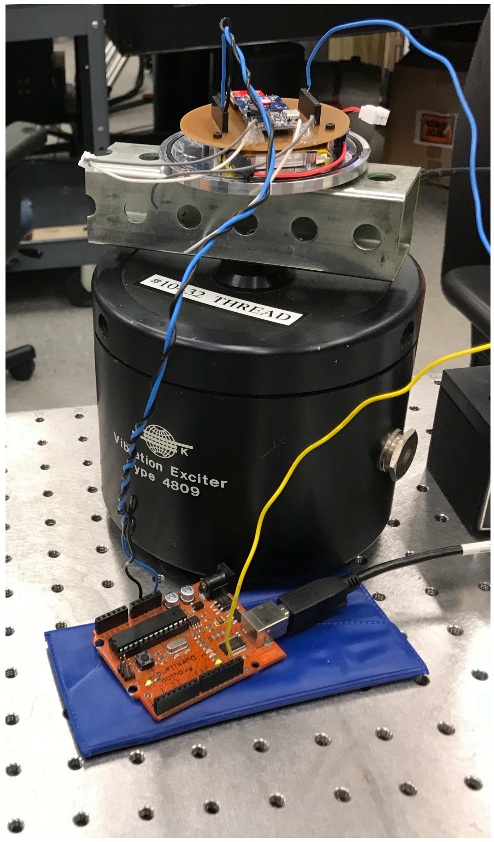

Figure 23 – Vibration test setup with shaker machine. Rectangular mounting tube, and WASP sensor pack. Baseline accelerometer not displayed.

The WASP sensor pack was magnetically mounted to a 75mm by 75mm rectangular hollow tube, as it would be magnetically mounted to a machine. The rectangular tube was mechanically bolted to the shaker machine, displayed in Figure 23, and oriented such that only the Z-axis of the WASP accelerometer would be excited.

A known reference accelerometer was used to verify the validity of our measurements. The accelerometer was rated for accuracy up to at least 20kHz. It was mounted on top of the WASP sensor pack so that it would pick up any system response caused by the WASP structure. The reference accelerometer is displayed in Figure 24.

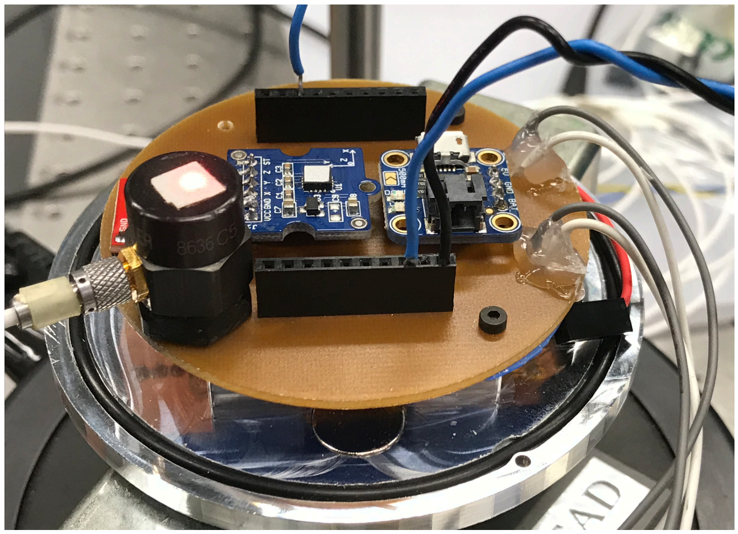

Figure 24 – Reference accelerometer mounted on top of WASP sensor pack to serve as a baseline for measuring structural response to excitation frequencies.

8.4 Experiment #1 – Baseline

The first test conducted was a baseline measurement. The laser velocimeter was centered on the reference accelerometer, displayed as a red dot in Figure 24. In the baseline test, only data from the reference accelerometer was collected, and the WASP accelerometer was ignored.

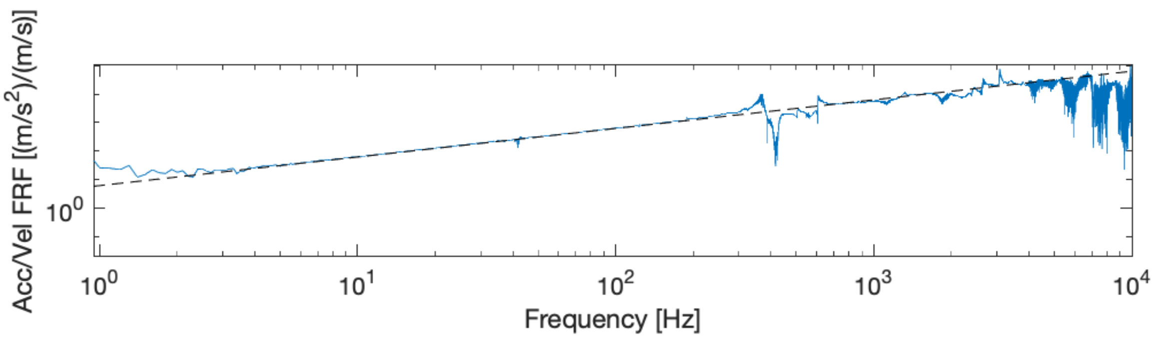

Figure 25 – Baseline measurement with reference accelerometer. Log-Log plot of acceleration/velocity.

The results of the baseline test are presented in Figure 25. We divide the acceleration measured by the reference accelerometer by the velocity measured by the laser velocimeter. This results in the Frequency Response Function, or transfer function, showing the response of the system to at varying frequencies. The x axis is plotted in units of Hz, or seconds^{-1}. The y axis is plotted in units of acceleration divided by velocity, similarly seconds^{-1}. Both axis are plotted as the logarithm of the units. The dotted black line denotes an ideal response, where the input frequency exactly matched the output frequency. In an ideal setting, the blue line denoting the reference accelerometer would exactly match the black line, denoting the identical response. In our baseline test, the reference accelerometer very closely matches ideal response, verifying that a successful frequency was generated, transmitted through the WASP structure, and measured by the reference sensor.

Typically, these results are displayed on a semi-log plot with the x-axis displayed in linear frequency input and the y-axis displayed in log of frequency. The graph in Figure 25 is replicated with a semi-log plot in Figure 26.

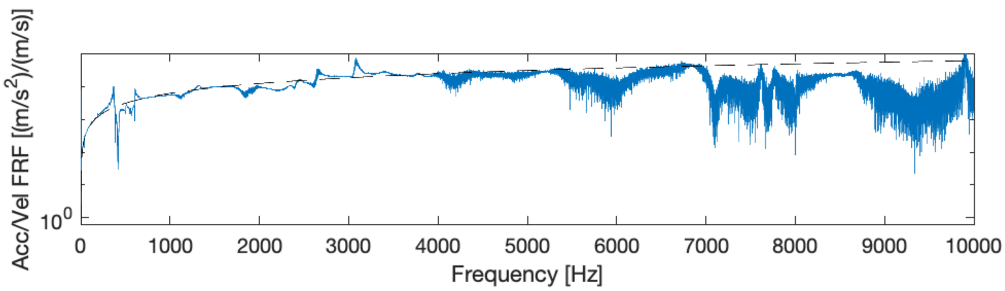

Figure 26 – Semi-log plot of baseline measurement with reference accelerometer.

The semi-log plot is convenient for interpreting the frequency response of the system. Interestingly, our reference accelerometer measured a resonant structural response at approximately 500 Hz and between the range of 2000 – 3000 Hz. This in indicated by a departure of the blue line (reference accelerometer) from the black line (ideal response.)

These results indicate that the structural design of the WASP resonates to some extent near the range of these input frequencies, and vibration measurements around these frequencies may be distorted.

Our second baseline test verified that we were receiving data from the WASP analog accelerometer. The second baseline was set up identically to the first, but with the laser velocimeter instead aimed at the WASP accelerometer. The results are displayed in Figure 27.

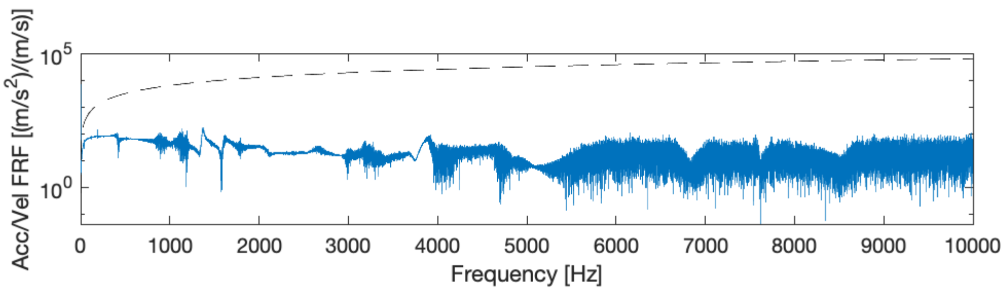

Figure 27 – Baseline with WASP accelerometer. Semi-log plot with frequency along the x-axis and log frequency along the y-axis.

Immediately, we notice the discrepancy between the ideal output and the WASP accelerometer measured output. Whereas the blue measured response should closely match the ideal response (except possibly at the frequencies or structural resonance) our measured response is significantly different from the ideal response at virtually all frequencies.

However, our baseline test cannot definitely provide a measure of the accuracy of the WASP accelerometer because data was only taken from one accelerometer during each of these tests.

8.5 Experiment #2 – Simultaneous Accelerometer Measurements

To verify the discrepancy unexpectedly found in our baseline tests, an experiment was set up to measure the acceleration of both accelerometers simultaneously while exciting the structure. In this test, an identical input was given to the system, white noise containing frequencies up to 10kHz. The experiment was replicated 10 times and the frequency response averaged.

The laser velocimeter was aimed at the reference accelerometer to measure the actual change in velocity of our reference accelerometer. By choosing to measure the reference accelerometer's physical velocity while recording its measured acceleration, we have a verified response profile against which we can compare the simultaneous WASP accelerometer measurements. In other words, we have a measured and verified reference that records the WASP system response to vibration. We also have the WASP accelerometer measurements recorded simultaneously. The comparison of these two measurements provides us a comparison of accuracy and quality between the two accelerometers.

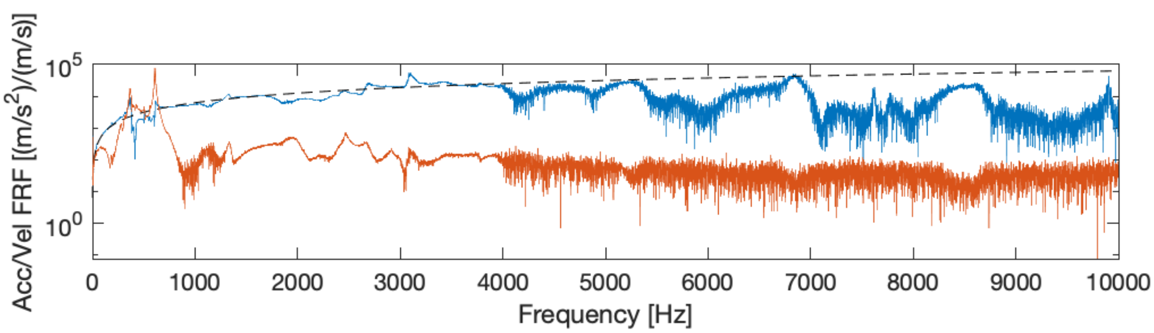

Figure 28 – Frequency response of simultaneous acceleration measurements of both reference accelerometer (blue) and WASP accelerometer (red). A significant discrepancy is observed between the reference accelerometer and the WASP accelerometer.

The results of the simultaneous frequency response measurements are displayed in Figure 28. A clear and significant difference in frequency response is observed between the reference accelerometer, denoted in blue, and the WASP accelerometer denoted in red.

To add an additional degree of confidence in our results, the coherence and phase shift of the signals were plotted in Figure 29. The coherence of the signals is a measure of power transfer between to signals. A coherence of 1 indicates that the input and output signal were both strong, while a coherence of zero indicates that the signal was very poor. The phase shift provides a measure of delay in the signals. In an ideal response, we would measure a phase shift of 90 degrees between the acceleration and velocity measurements.

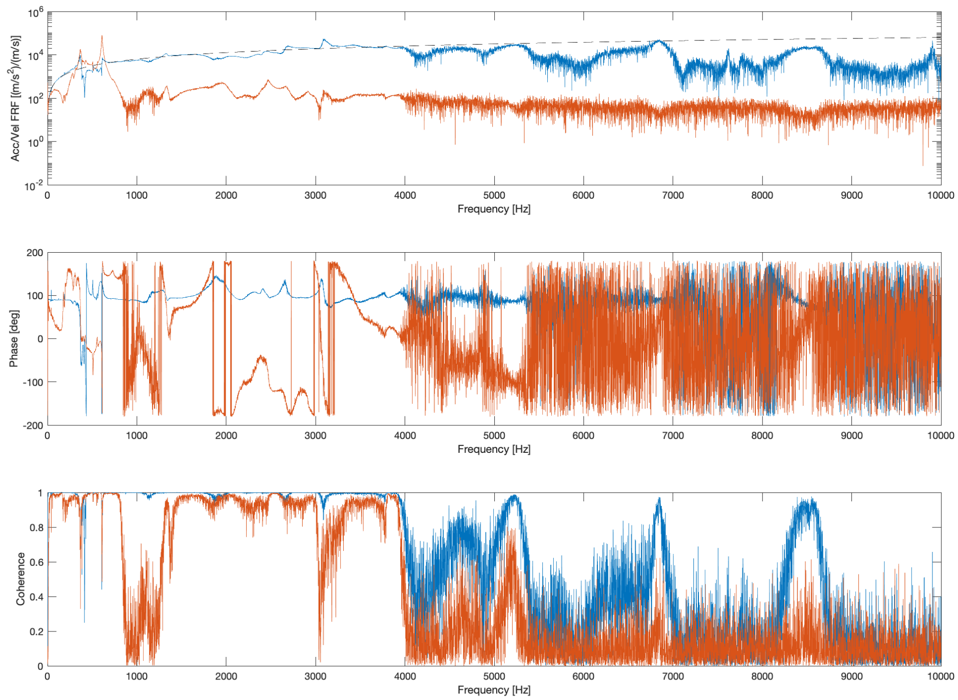

Figure 29 – Simultaneous frequency response of the reference accelerometer and WASP accelerometer with phase shift and coherence.

For frequencies up to 4000 Hz, the coherence value is near 1, indicating that we received a valid signal for the majority of this range from both accelerometers. However, the phase shift indicates a discrepancy between the ideal 90 degree shift observed in the reference accelerometer (except at 500 Hz during the structural resonance) and the inconsistent phase shift of the WASP accelerometer. This further supports our initial results of very poor accuracy of the WASP accelerometer.

To ensure that the x-axis and y-axis were not contributing to the z-axis measurements, two additional experiments were conducted under identical circumstances, but while measuring the x-axis and y-axis of the WASP accelerometer instead of measuring the z-axis response. The results of the x-axis and y-axis measurements are presented in Figure 30 and Figure 31 respectively.

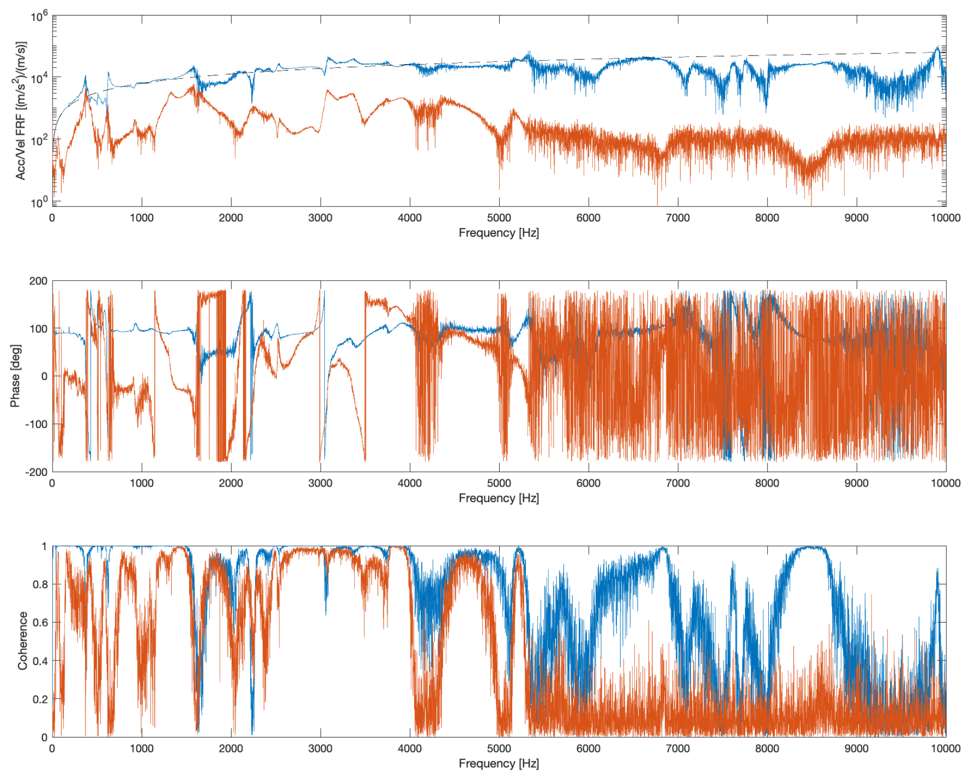

Figure 30 – Simultaneous z-axis reference accelerometer and x-axis WASP accelerometer measurements with signal coherence and phase shift.

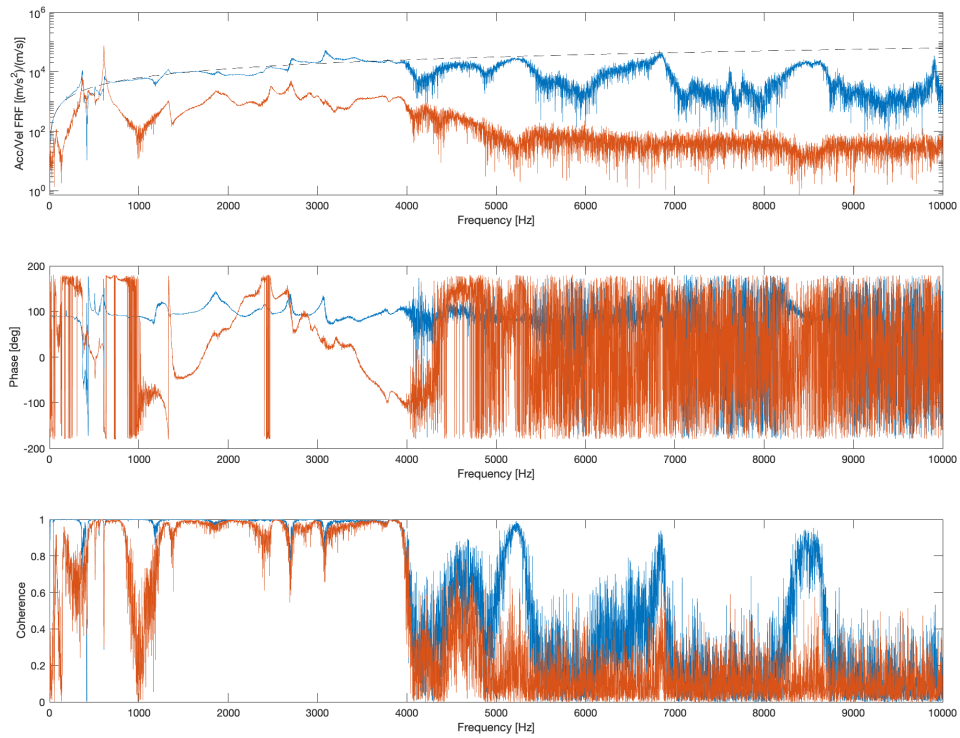

Figure 31 - Simultaneous z-axis reference accelerometer and y-axis WASP accelerometer measurements with signal coherence and phase shift.

8.6 Experiment #3 – Elimination of Mounting Effects

To eliminate the effects of the rectangular tube to which the WASP sensor pack was mounted, a third experiment was conducted with the WASP sensor pack mounted directly to the shaker machine. In the first test of this experiment, the laser velocimeter was aimed at the WASP accelerometer to measure its physical velocity. The simultaneous frequency response of both accelerometers is displayed in Figure 32.

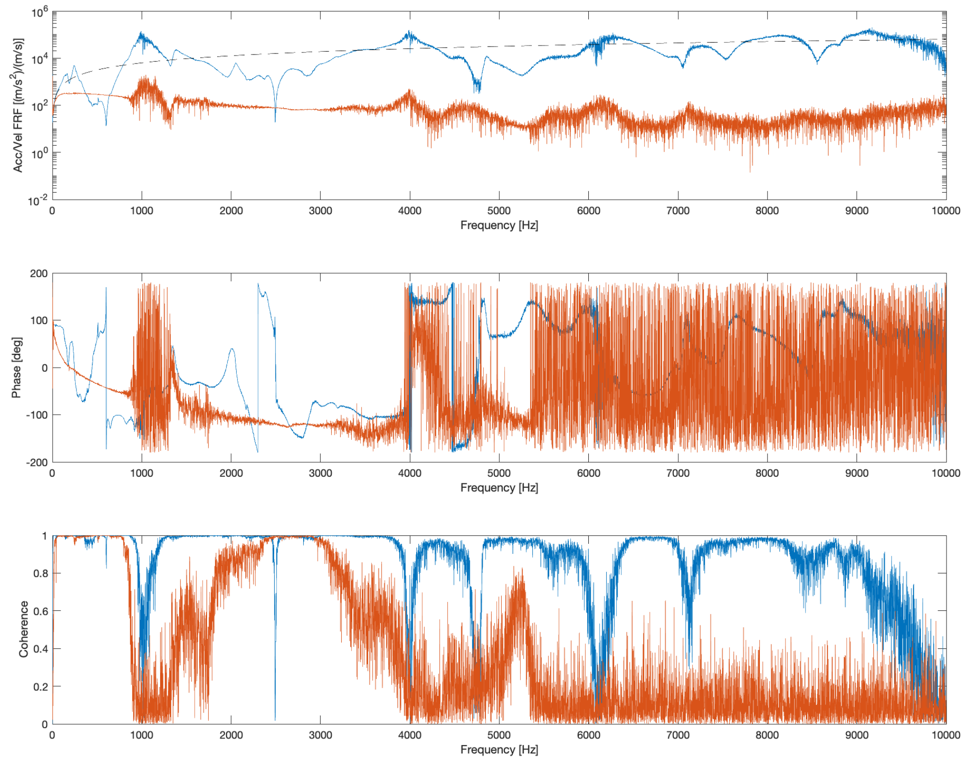

Figure 32 – Experiment #3 frequency response measurements with laser velocimeter aimed at the WASP accelerometer to measure its physical velocity. Slight variances from the ideal response are observed in the reference accelerometer (blue) because the velocimeter was not directly measuring its velocity.

In the second test of this experiment, the laser velocimeter was aimed at the reference accelerometer, displayed in Figure 33. A near ideal response is measured from the reference accelerometer.

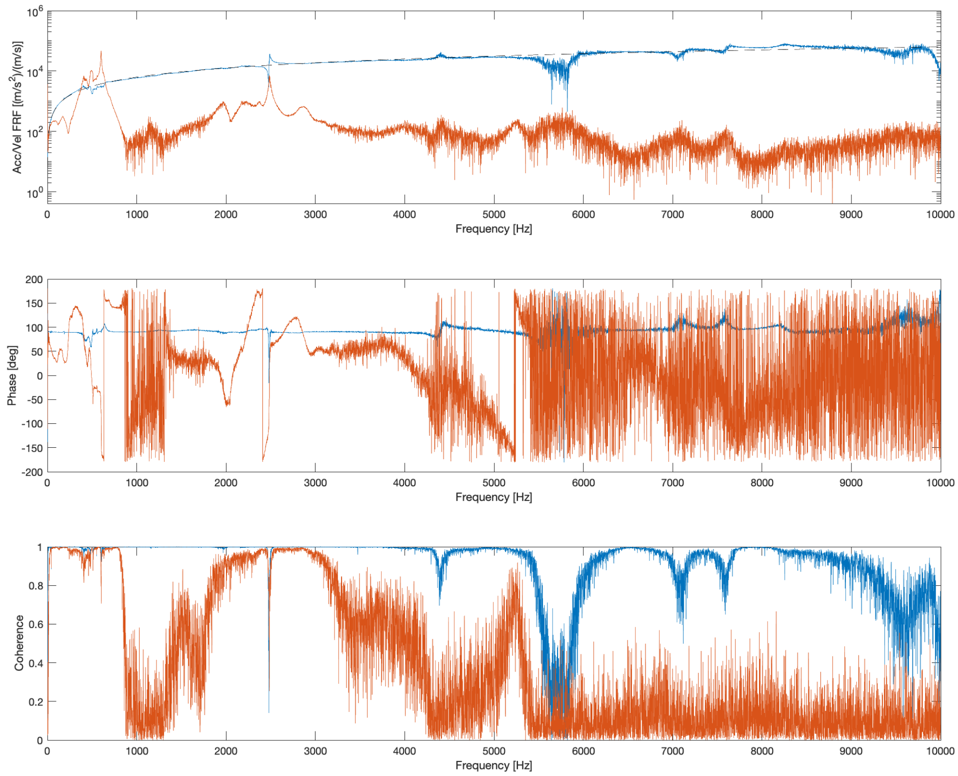

Figure 33 – Experiment #3 frequency response measurements, identical to previous test, except with laser velocimeter aimed at reference accelerometer. A near ideal response is measured from the reference accelerometer.

8.7 Overall Evaluation

In summary, the Groove ADXL335 performed very poorly. While there were some frequency ranges of comparable accuracy, there were also ranges where it appeared that the sensor measured a full derivative difference from the input. Although the accelerometer measured acceleration, it appeared to provide an output that more closely matched the velocity of the sensor pack. In other words, this accelerometer was extremely inaccurate over most ranges of vibration. Our result is unfortunate in terms of low-cost requirements for creating the WASP sensor pack, but also provides valuable insight into what is needed to make the high-quality analytic capability of the WASP a reality.

CHAPTER 9. RESULTS

9.1 Deployment on Manual Lathe

The WASP sensor pack was verified for functionality on a Harrison manual lathe. Data collection was acquired through sampling of the analog ADC and The WASP was triggered to collect data wirelessly.

The WASP was magnetically mounted to the front face of the selectable gearbox where users identify the desired spindle RPMs and auto-feed configuration through the combination of engaged gears. The WASP mounting configuration is displayed in Figure 34.

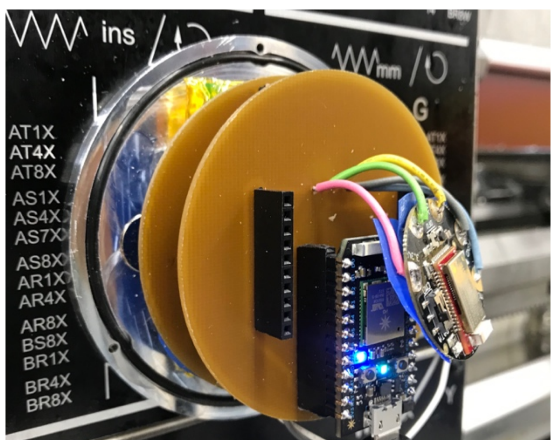

Figure 34 – WASP mounted to the front gear panel of a Harrison manual lathe for vibration measurement.

The spindle of the manual lathe was set to 2500 RPM, and the auto-feed was set to 0.6mm per revolution. The analog accelerometer was set to record 500 samples on a single axis channel oriented parallel to the surface of the accelerometer, at a frequency of 66kHz.

Each data point was an average of 28 ADC samples, completed in a nominal 933ns period. A time stamp of each the data point was also taken to verify sample frequency. The results of the analog accelerometer are presented in Figure 35.

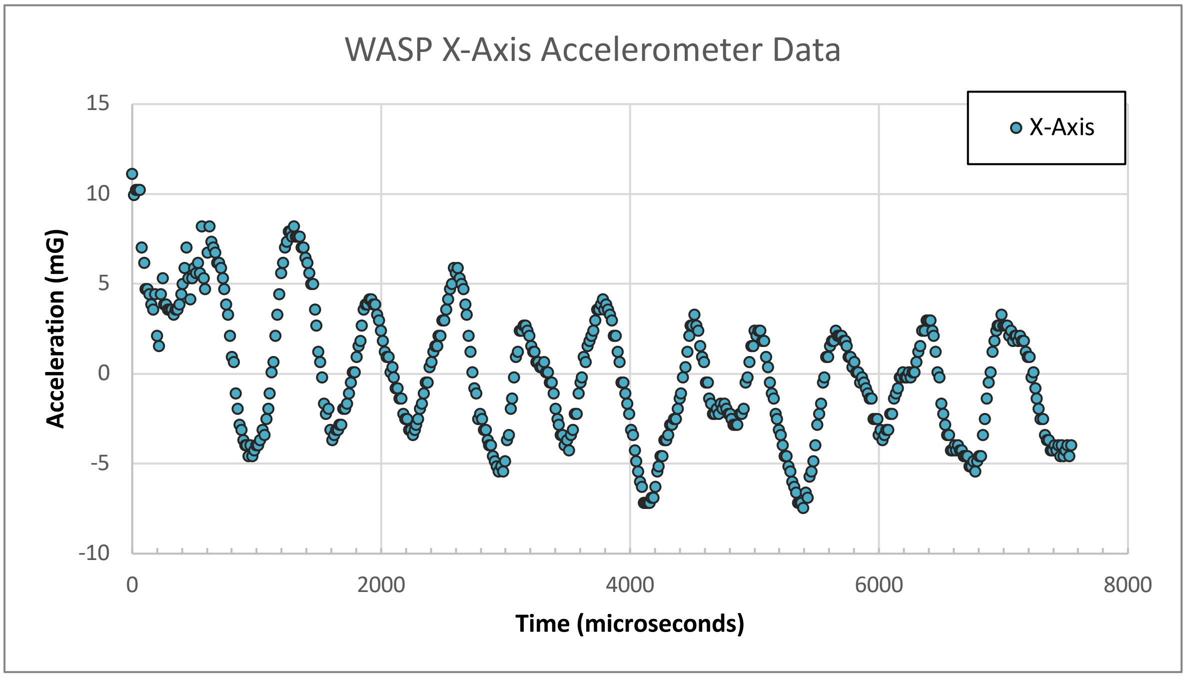

Figure 35 – X-axis accelerometer data taken measured with the WASP on a Harrison manual lathe with spindle RPM of 2500. Measured RPM calculated approximately 1700 RPM. Measure RPM is likely from a mechanically linked internal gear.

Surprisingly, a frequency of approximately 1700Hz was recorded by the analog accelerometer. On further analysis, it was determined that the sensor pack may have measured the rotations on a gear internal to the lathe, not the main spindle frequency. Due to the placement on the gear panel, one particular gear connecting the spindle RPM and the auto-feed setting may have dominated the vibration pattern at this location, resulting in the accelerometer's measurement.

CHAPTER 10. CONCLUSIONS

The Wireless Accelerometer Sensor Platform (WASP) provides a modular and robust solution to monitor machine health. The WASP provides a low-cost implementation with powerful data acquisition and analytic capability. Furthermore, the WASP provides the flexibility for sensor and component expansion, adapting to meet the needs of a wide range of manufacturing equipment.

Placement of the WASP on a machine is of clear importance to proper functioning of the device. In the case of vibration measurement, careful placement of the WASP on the machine is critical to quality data acquisition. The WASP provides the capability to communicate with mobile devices through the Bluetooth LE functionality, and the WASP Connect provides a verification process to ensure proper vibration measurement. With this capability, the WASP provides significant, low-cost, and quality diagnostic capability for many manufacturing environments.

It was demonstrated that the standard analog accelerometer is a viable sensor for low-frequency measurements, but a higher quality accelerometer is required for high frequency measurements. This accelerometer can meet the needs of some machining operations, but an auxiliary accelerometer is needed for higher RPM spindles. One potential recourse for high quality measurements is provided in the modular flexibility of the WASP. Additional higher-quality accelerometers could be included as an auxiliary jacket for high frequency vibration measurements.

CHAPTER 11. FUTURE WORK

One remaining difficulty in setting up the WASP is linking data collection to the exact machine on which the WASP is placed in the digital machine monitoring architecture created at GT. While it only requires a few changes in the code configuration, this is too involved for the user if the sensor is deployed to a machine shop. Instead a convenient method is needed to identify the data coming from the WASP, and label it as coming from a specific machine in the digital architecture.

This could be achieved through the use of uniquely identifying QR codes on the machine in question and on the sensor. The monitoring app could be expanded to take a picture of the QR code on the deployed sensor, the QR code identifying the machine on which the sensor is deployed, and automatically link data collection to a storage database in the cloud. This would provide a convenient method to identify on which machine the sensor was placed, and digitally identify the data collected from that machine in the database storage system.

Additionally, a usability study needs to be conducted with the WASP Connect App. The usefulness of the app is directly related to how well a user intuitively understands its interface and understands how to use the app in their own specific manufacturing process. A usability study would provide valuable feedback to determine interface changes, unexpected use cases, and potential failure points in the intended flow of the app. This information could be used to greatly improve the apps reliability, flexibility, and increase its successful adoption.

APPENDIX A. BILL OF MATERIALS

%	Est. Production Cost	Part	Hobby Cost	%
22%	$9.75	Aluminum Stock	$26.25	22%
34%	$14.95	2200 mAh Li-Po Battery	$14.95	13%
1%	$0.43	Battery Charger	$6.95	6%
9%	$4.00	Inductive Coil	$9.95	9%
8%	$3.44	Analog accelerometer	$10.01	9%
2%	$1.06	Digital accelerometer	$9.95	9%
21%	$9.31	Particle Photon	$19.99	17%
0%	$0.00	Flora BLE Module	$17.50	15%
1%	$0.30	O-ring	$0.61	1%
1%	$0.38	Fastening hardware	$0.78	1%
	$43.62		**$116.94**	

Bill of materials including cost of components when purchased through hobby stores, and projected cost of components when purchased in large quantities for production of WASP sensor pack. Percent of total cost included for both hobby cost and production cost estimate.

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